National Aeronautics and Space Administration

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# Assessing the Altimetric Measurement with CyGNSS Data

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IGARSS, Valencia, Spain - July 27 2018

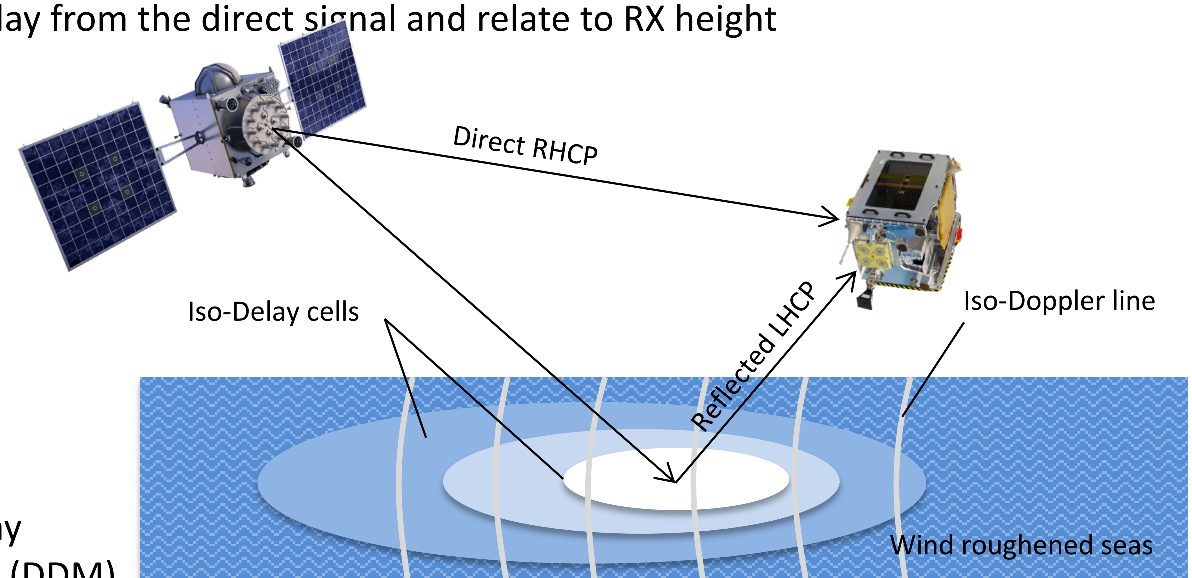
# Outline

- Altimetry with GNSS-R
- CyGNSS data
- Determining SSH
- Region of study
- Preliminary results
- Next steps

# Description of GNSS-R Altimetry Measurement



- Track the specular reflection point (SRP) path delay from the direct signal and relate to RX height above reference surface
- Delay anomaly, $\Delta\delta = (\delta_{measured} - \delta_{modeled})$




- Received power contains contributions from the SRP (shortest path) together with those from an area of the ocean around it, the glistening zone

- Received power is expressed in the space of delay and Doppler and is output as delay Doppler map (DDM)

- The altimetry measurement is reduced to the accurate determination of the minimum path delay in the DDM

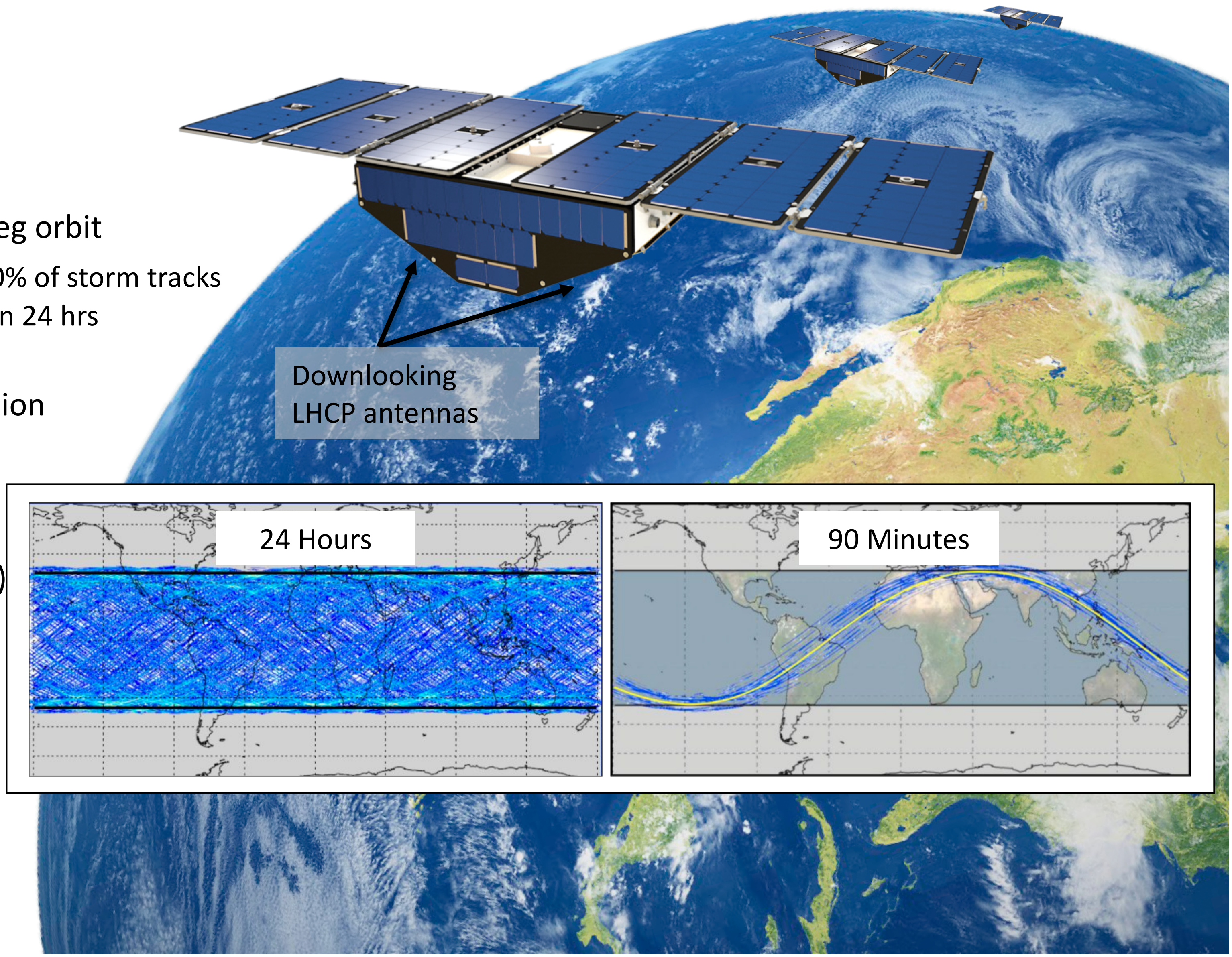
Received Power at antenna:

$$P_R = \frac{P_T\ G_T\ \lambda^2}{(4\ \pi)^3\ R_{TS}^2} \int_A \frac{G_R\ \sigma^0}{R_{RS}^2} dp$$

# Overview of the CyGNSS Constellation

**CyGNSS**

- Launched Dec 2016
- 8 spacecraft in ~35 deg orbit
- Required to sample 70% of storm tracks between ±38 deg within 24 hrs
- 1Hz DDM generation and real-time navigation with GPS L1 C/A
- 4 channels from 2 down-looking antennas (15 dB gain)

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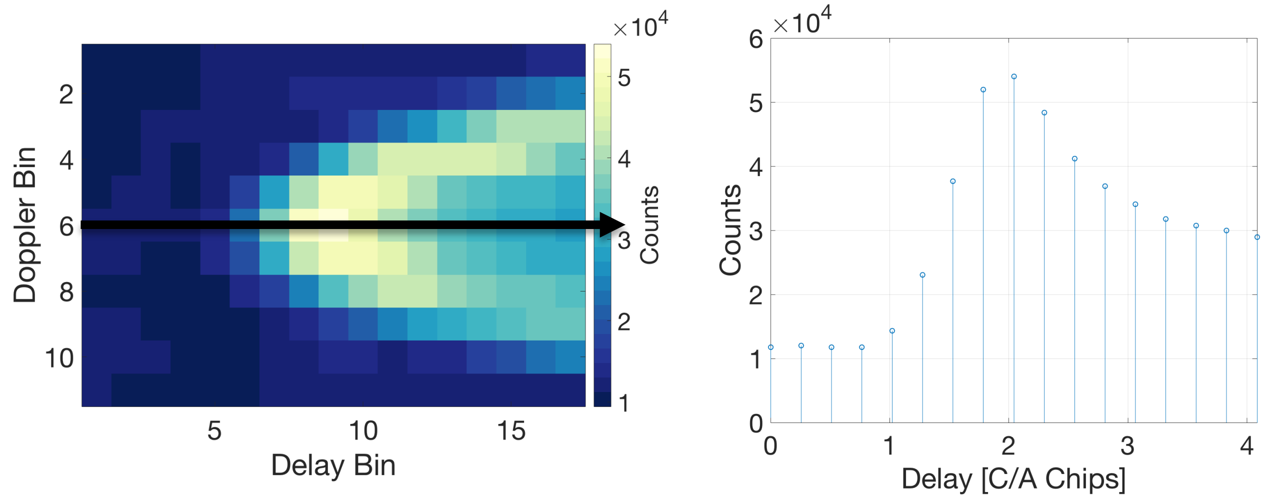
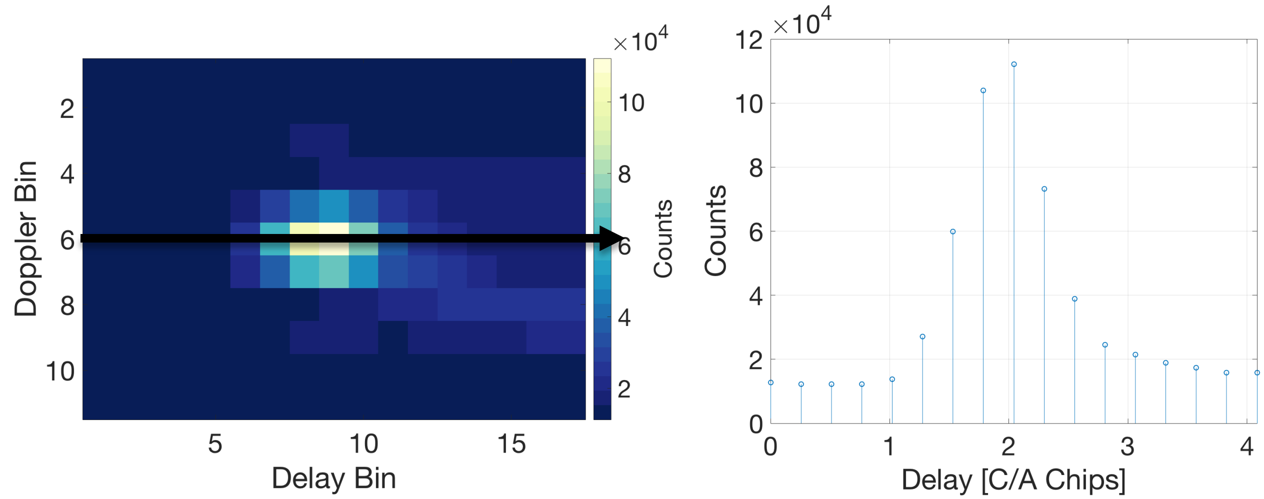
# CyGNSS – Delay Doppler Maps

- DDM samples are cropped in delay and Doppler and offset from the direct signal tracking used for real-time navigation.
    - For altimetry we need relative delay
- CyGNSS observes coherent and incoherent reflections depending on the ocean surface conditions

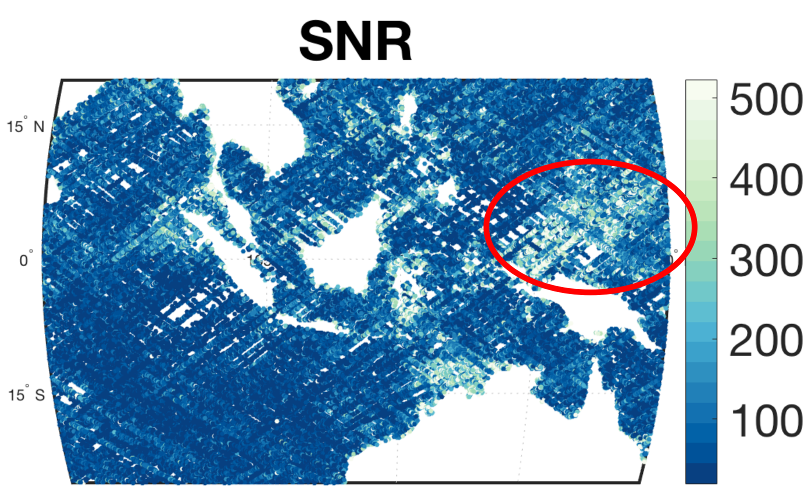


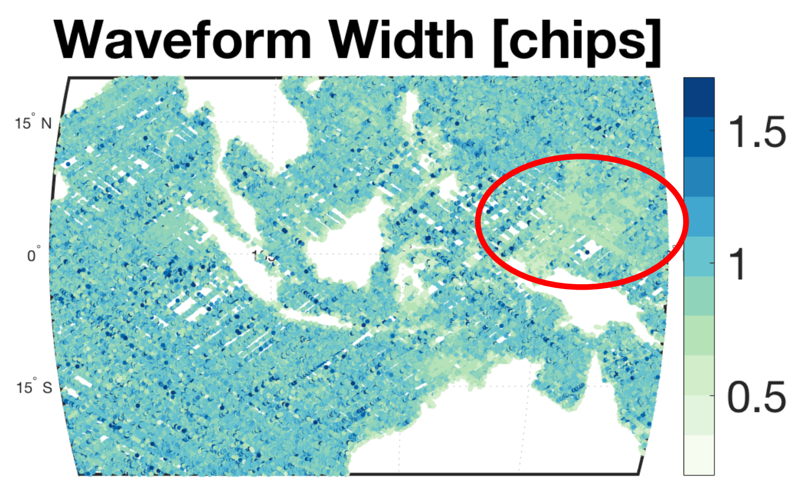

- High wind > rougher seas > incoherent reflection spread across larger delay/Doppler space
- Low wind > smoother seas > coherent reflection concentrated in small area
    - Waveform looks more similar to direct signal waveform



# CyGNSS Observations in Indonesia

- Many points are observed to have predominantly coherent characteristics, corresponding to high SNR
  - Use SNR and Waveform Width as metrics for coherence
    - $\text{SNR} = (\text{Amp}_{peak} - \text{Amp}_{noise}) / \sigma_{noise}$
  - Some regions yield narrow width and high SNR measurements (Peak power > 8 dB over incoherent) indicating strong coherence that is persistent over several days
- This region might represent a “sweet spot” to investigate the CYGNSS potential for altimetry since the high SNR distribution compensates for the antenna gain limitations



# Altimetry Delay Model

## Delay Model Components

Precise positioning – GIPSY Smoothing + IGS Final

Mean sea surface topography – DTU10/15

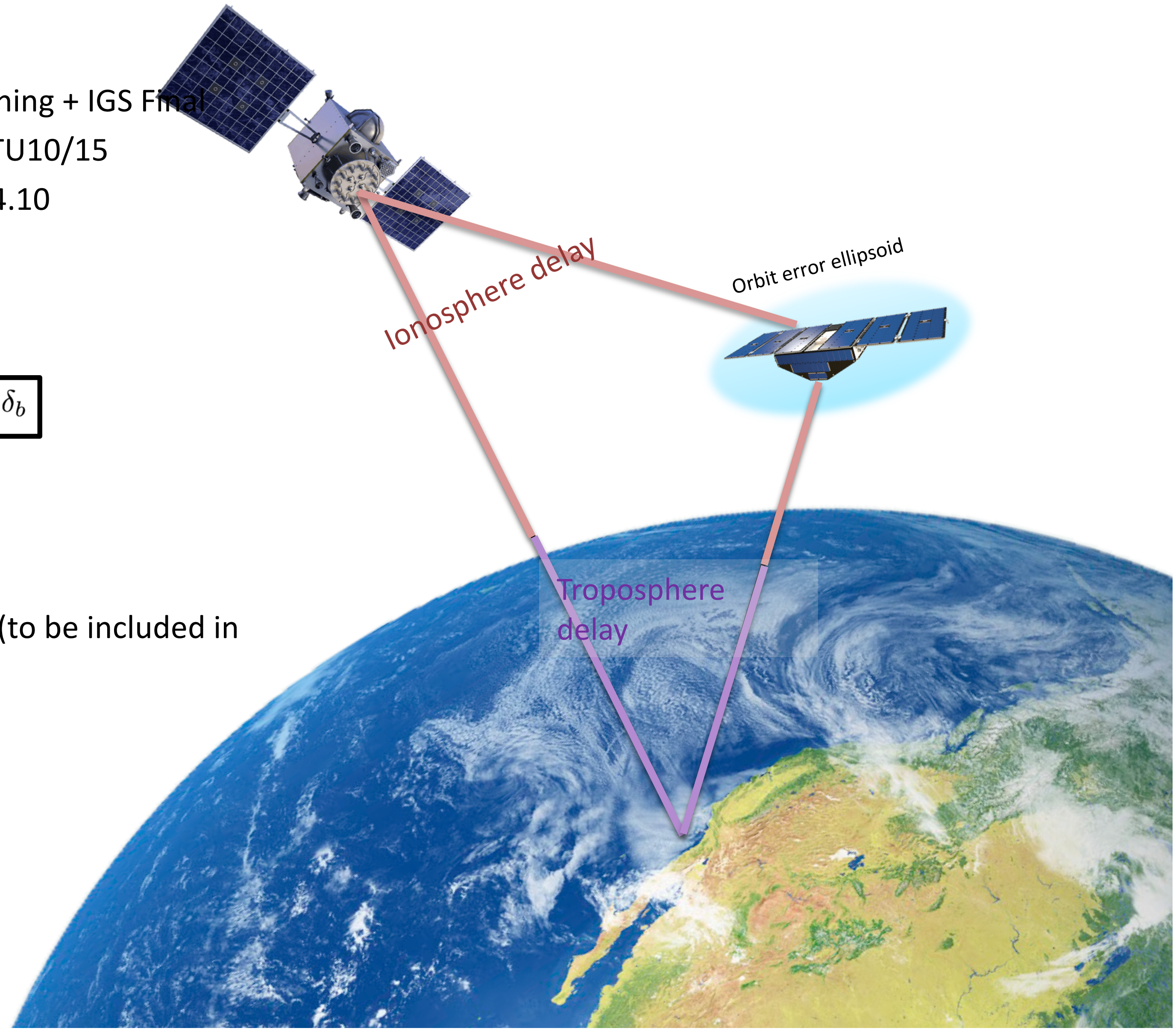
Ocean and solid body tides – GOT4.10

Ionosphere delay – IRI2012/GIM

Troposphere delay – UNB3m

Antenna baseline geometry

$$\boxed{\delta_{HiFi} = (\delta_R - \delta_D) + \delta_{iono} + \delta_{tropo} + \delta_b}$$




## Yet To Be Included

Significant wave height effects

Receiving antenna pattern effects (to be included in E2ES retrievals)

# CyGNSS Altimetry – Metadata

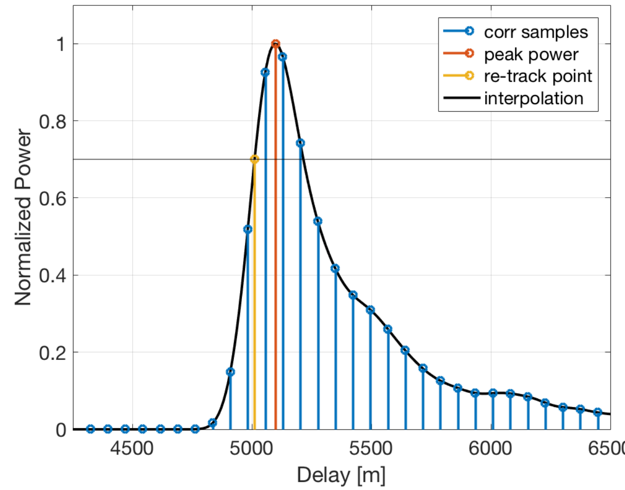
- Required metadata from the CyGNSS constellation includes
  - Precise time tagging of measurements (good quality)
  - CyGNSS orbit knowledge to correctly model position of the receiver at the time of signal reception (poor quality)
  - Knowledge of the nadir channel delay with respect to the zenith direct signal tracking channel (good quality)
- Real-time CyGNSS orbit estimates from onboard GPS L1 navigation solutions are provided
  - JPL is producing improved orbits using GipsyX to reduce noise in real-time solutions
  - Difference of ~3m RMS between GipsyX dynamic orbit fits and real-time solutions
- We gather/construct additional supporting data such as GPS orbits and expected specular reflection points using precise models
  - GPS final orbit solutions from IGS
  - DTU Mean Sea Surface models are used for prediction of specular point

# Altimetry – Delay Re-Tracking Algorithms



Point Tracking (on section of DDM @ 0 Doppler)

– **HALF** – Track X% on waveform leading edge, we chose 70%
– **DER** (historical)– Track peak derivative on leading edge



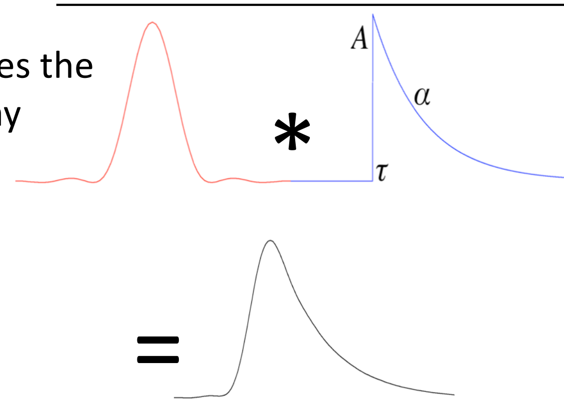

Waveform Tracking (on section of DDM @ 0 Doppler)

– **PARA3** – Empirical waveform model fit over 3 parameters, f(t | $\tau$, A, $\alpha$)
– **DER** - Fits a cubic spline to the data and takes the derivative of the fit with respect to the delay
– **VZ18** – Waveform fit based on model *

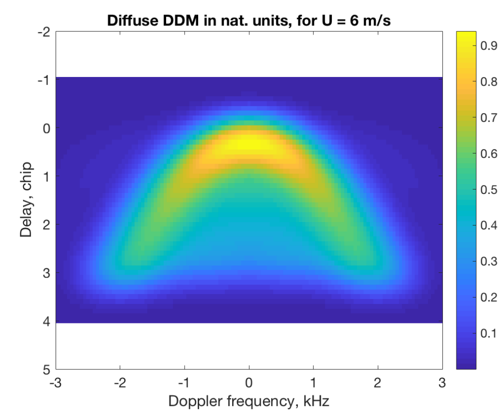
DDM Tracking (on entire DDM)

– **CyGNSS E2ES** – with scattering model *

*Physical scattering model from Voronovich and Zavorotny (2018)



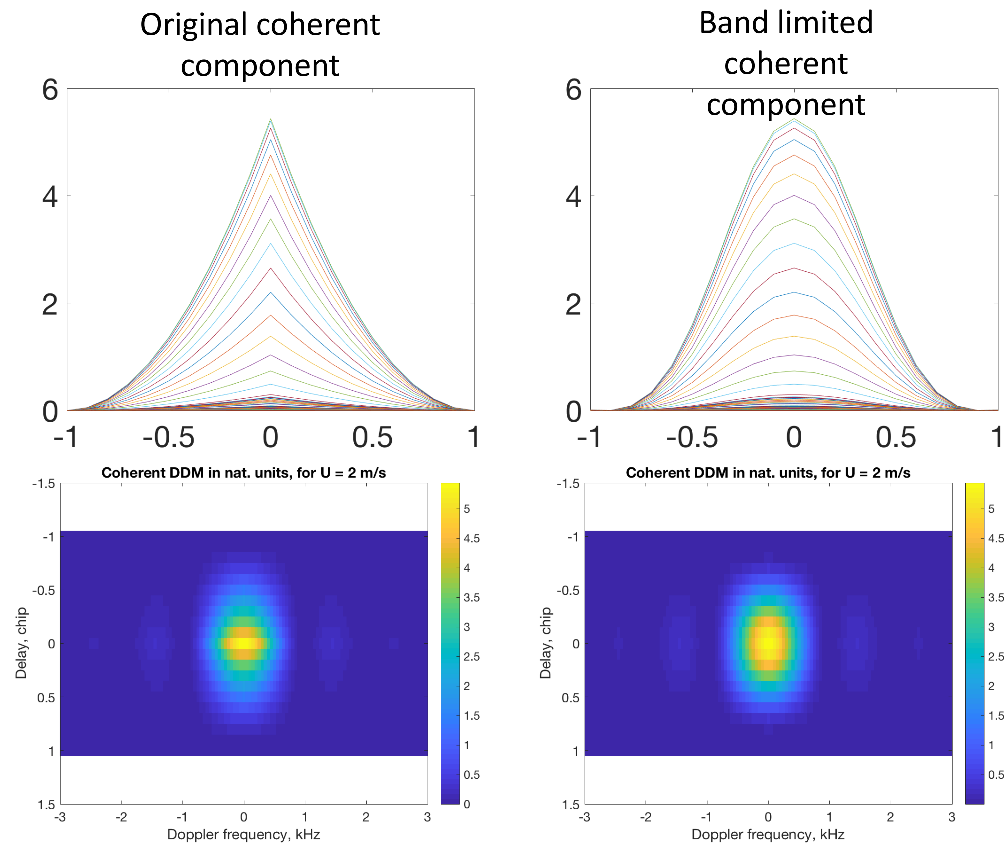

PARA3 Waveform Model




VZ DDM Model

# Algorithm Characteristics

- In Progress: Attempting to retrieve specular delay across array of coherent and incoherent reflections
  - Updated VZ model (2018) simulates both coherent and incoherent components
- We have added a bandlimited AC model to be representative of CyGNSS measurements

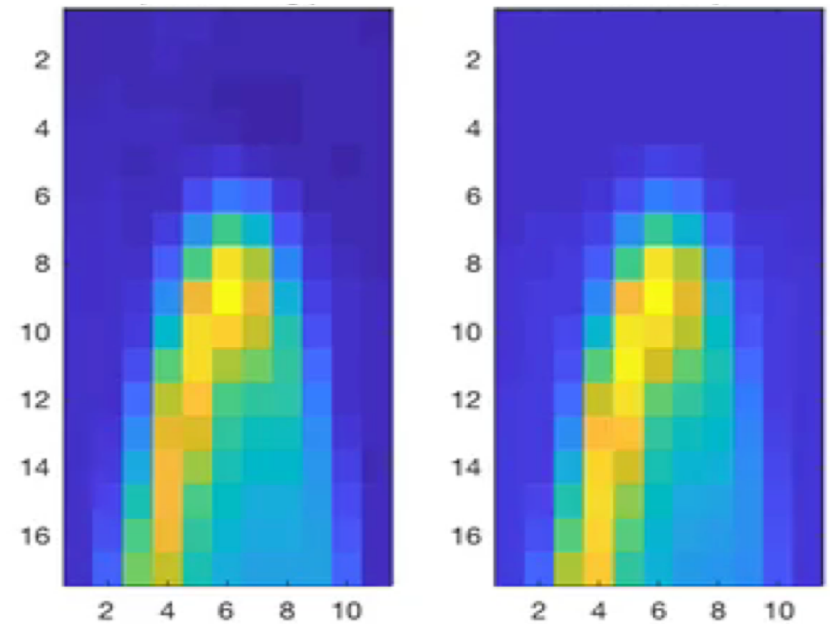


# E2E Fit Algorithm Characteristics

- The **CYGNSS End-to-End Simulator (E2E)** is capable of producing simulated DDMs that match very closely with on-orbit measurements
- We can use the E2E to find the parameters (altimetric delay offset, Doppler offset, wind speed, etc) that best fit each DDM measurement
- In the E2E Fit algorithm the calculation of the specular point is determined by minimizing the difference between the measured DDM and a family of simulated DDMs
- This allows us to **utilize the full DDM in the altimetry estimate** instead of just the peak
- If simulator model is accurate, this should result in a significant reduction in measurement error

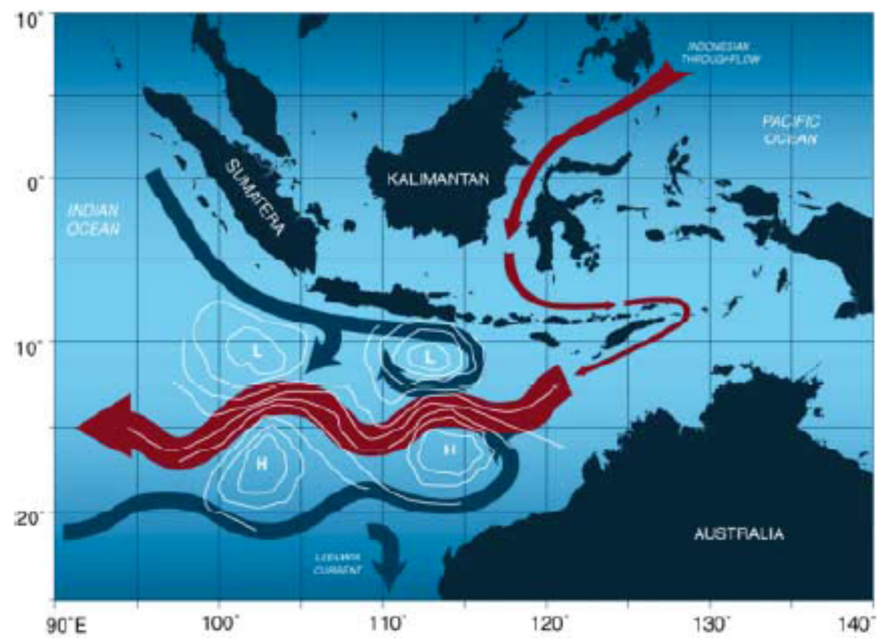
CYGNSS Measurement

Simulated Best Fit

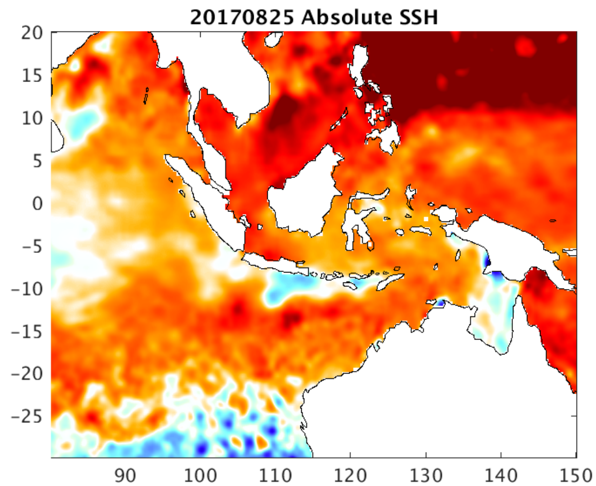


# Regional study - Indonesian Throughflow

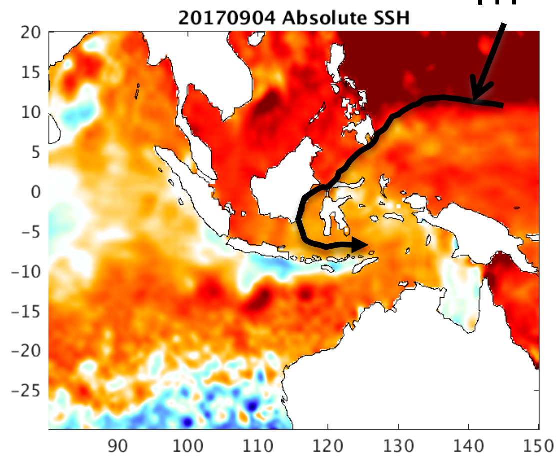
- System of surface currents flowing from the Pacific Ocean to the Indian Ocean through the Indonesian Seas.
- Important because it is the only low latitude transport between oceans
- Even more important because one of the oceans is the warm Western Pacific



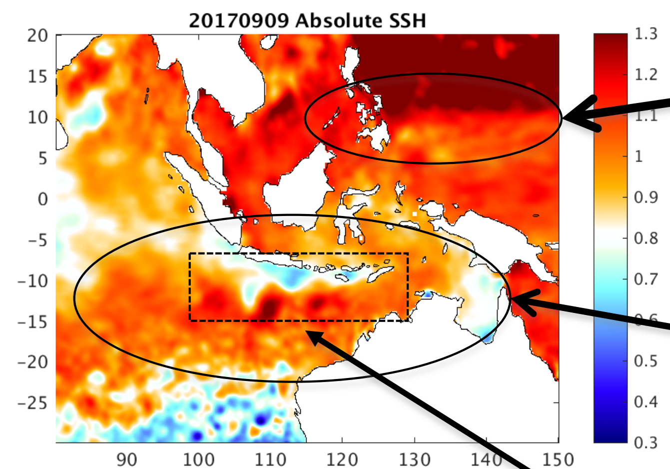
# Large Seasonal Signal Variation




ITF




September




Large SSH gradients, which is the driving forcing of the ITF

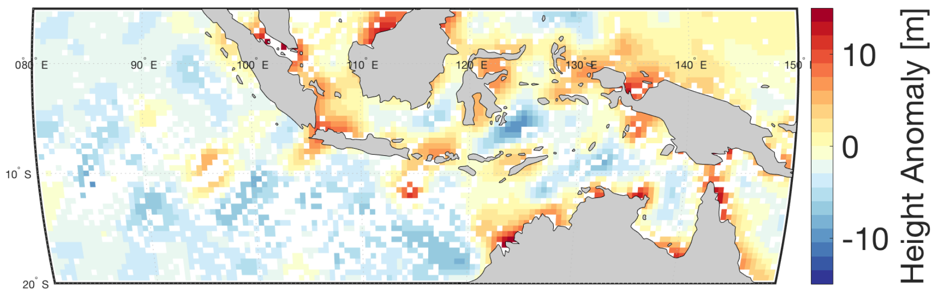
The anomaly changes signs between April and September. The change occurs in May.

The contrast in SSH anomaly between April and September is about 0.5m

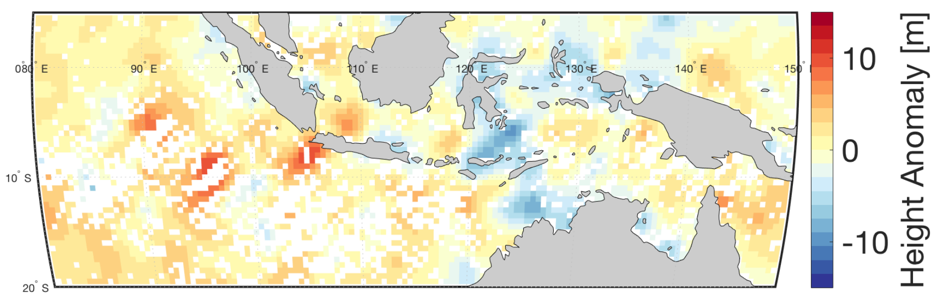
well-known mesoscale eddy train

# CyGNSS Altimetry Smoothed Retrievals

- 2deg FWHM Gaussian smoothed retrievals, data from August 18-22 2017




P70 1Hz
Applied to both coherent and incoherent reflections

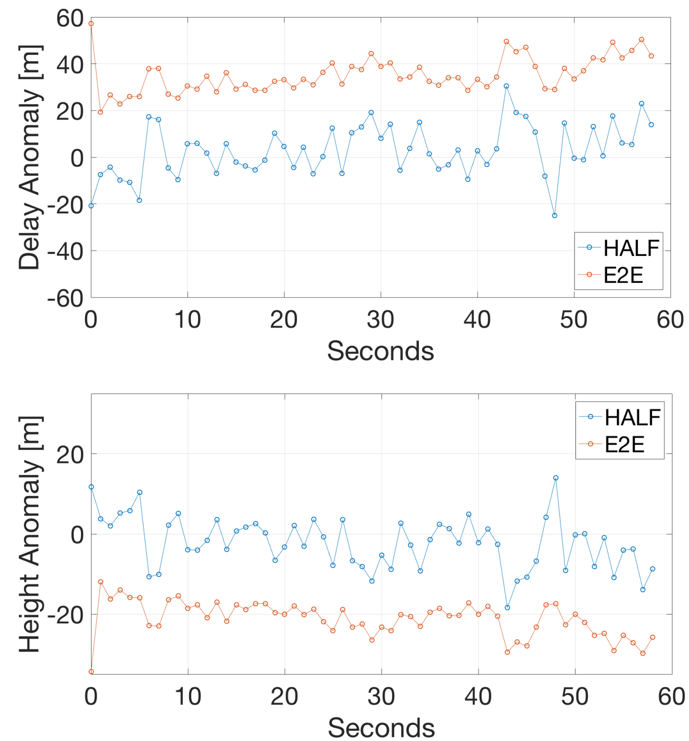



VZ18 1Hz
Applied to both coherent and incoherent reflections

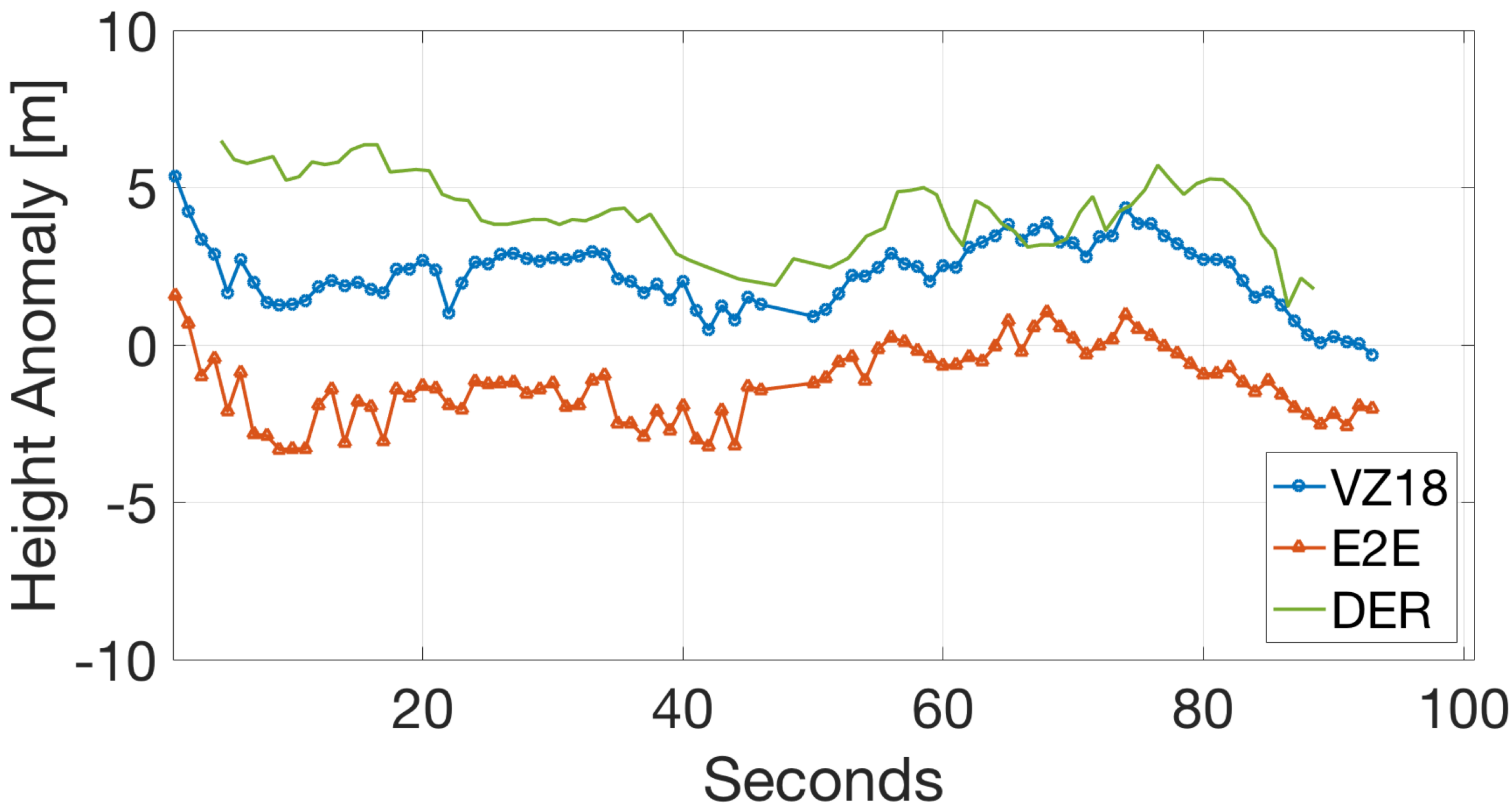
# Algorithm Performance Comparison (1)

- Examined one ~100 km track in Indonesia
- Data has been averaged over 10 sec

Comparison of Altimetric Retrieval Error



# Algorithm Performance Comparison (2)




Retrievals are based on 1Hz data averaged down to 0.1Hz

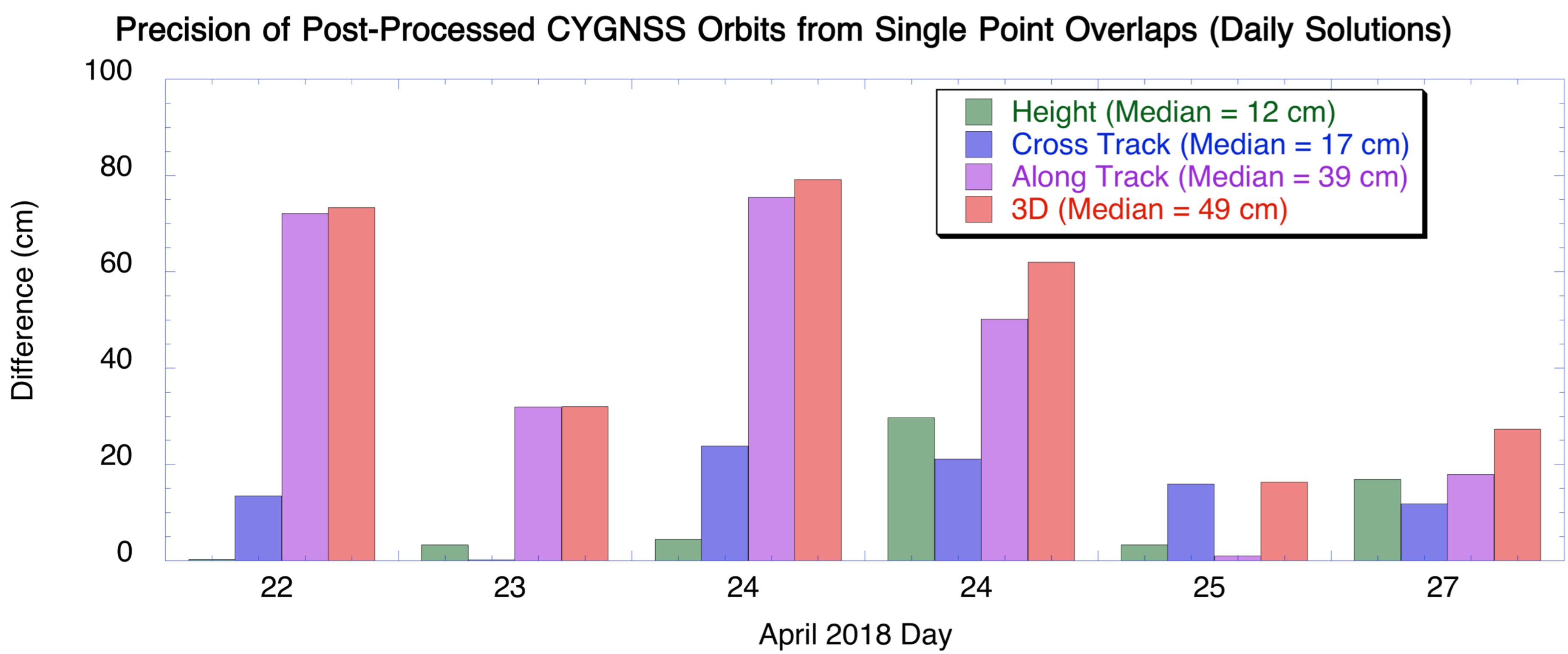
# Preliminary Error Budget

| Error Source | Uncertainty in Delay |
|---|---|
| CYG Orbit | 1.9 m (systematic) ; Nav solution rounded to nearest 1 m/s<br>***~50 cm postprocessing*** |
| GPS Orbit | 0.05 m (systematic) |
| Tides | 0.19 m (systematic) |
| Ionosphere | 4 m (day, RMS) ; Single frequency limitation<br>2.2 m (night, RMS)<br>***Using IRI; might be improved by GIM*** |
| Troposphere | 0.05 m (RMS) |
| Antenna Baseline | 0.002 m (systematic) |
| Tracking Error | 0.9 m (VZ18, RMS)<br>1.2 m (E2E, RMS) |
| RSS | ~4.5/~3 m (day) (night) |

Based on analysis in Indonesia

# CYGNSS Post-Processing Orbit Determination

- Based on seven days of tracking data (April 21–27, 2018) returned from FM04.
- Use CA pseudorange (code) data in JPL GIPSY software (inclusion of L1 phase data pending).
- Use precise GPS satellite orbit and clock products (JPL contribution to IGS).
- Use high-fidelity (GIPSY) models of geopotential (70 X 70), solar radiation pressure and drag.
- Correct for code biases using IGS standard estimates (CA vs. P1, CA vs. PC).
- Correct for ionosphere using technique developed for TOPEX/Poseidon single-frequency GPS:
  - Use JPL GIM to provide vertical ionosphere delay, and scale to CYGNSS altitude using vertical profile shape based on BENT.
  - Integrate up (in piece-wise fashion) the delay along each line of sight.

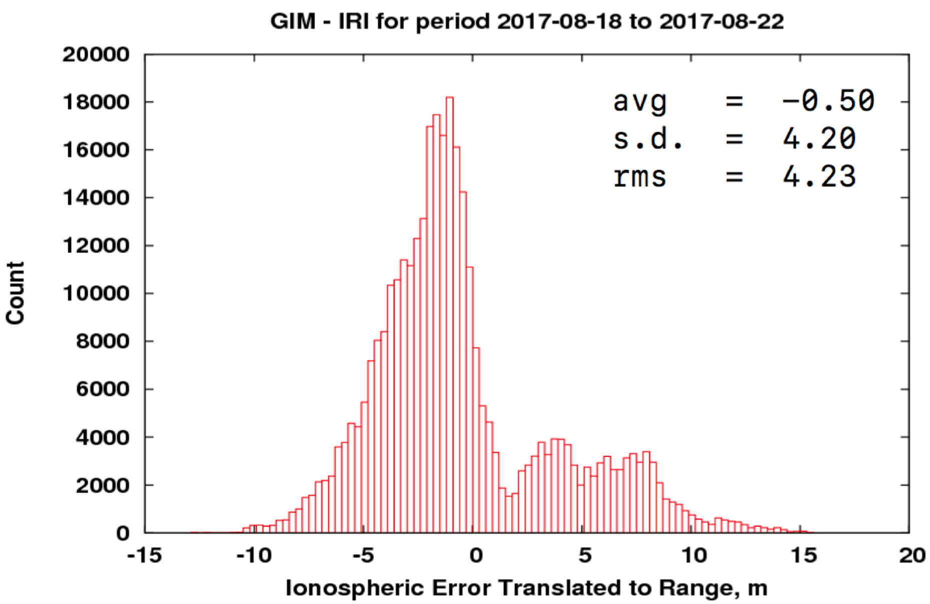


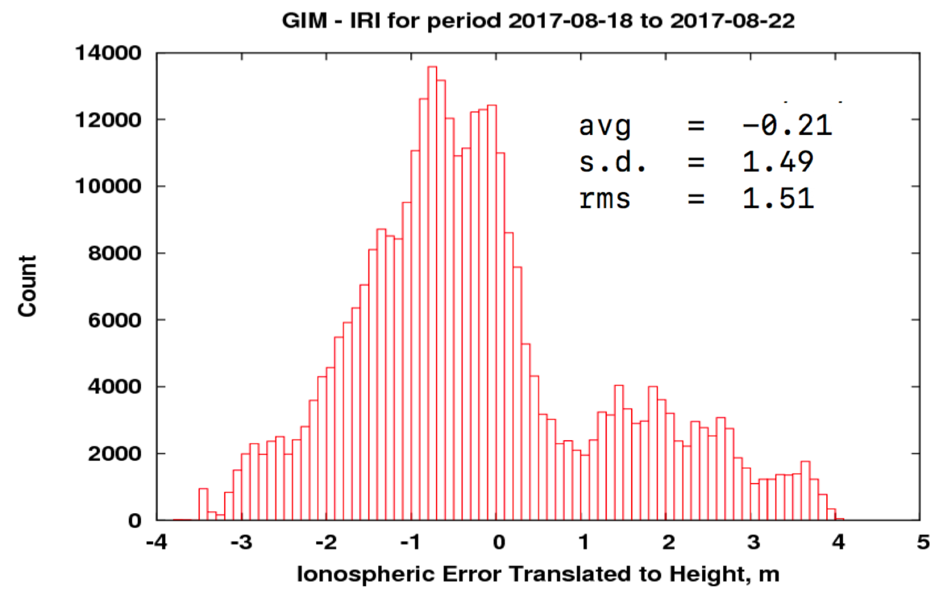
# Orbit Correction – Next Steps

- Single point overlaps suggest that accuracies < 1 m (3D, 1$\sigma$) achievable using tracking observables and post-processing techniques.
  - Precision of ~50 cm based on single point overlaps.
  - Approximate 5X improvement over accuracy of onboard navigation solution, but….
  - Small number of samples (6 single point overlaps from 7 daily solutions) implies caution is warranted.
- Further potential improvements to be studied:
  - Incorporate L1 carrier phase
  - Incorporate spacecraft attitude data (e.g., to account for phase windup).
  - Try GRAPHIC observable (CA – L1) to remove ionosphere (as alternative approach to modeling).
  - Use high-frequency (1-Hz) data to improve editing and strengthen solution.
  - Tune reduced-dynamic orbit determination strategy.

# Modeling the Ionosphere GIM-IRI






- Period covered: 2017-08-18 till 2017-08-22
- Region: -20 to 5 deg. north latitude, 80 to 150 deg. E. Longitude
- Shown are histograms of GIM – IRI ionospheric delay in range for all bi-static links (left) and corresponding sea surface height error (right)
- Ionospheric height error is estimated at ~1.5m RMS

# Next Steps

**New Algorithms Implementation**

- Finalize assessment of algorithms to find solutions in both regimes of coherent and incoherent reflections by performing a large scale run in Indonesia to observe detectability of seasonal signature
- Preliminary results indicate our E2E Fit algorithm could offer an improved SSH estimate; this algorithm is computationally intensive and will likely require supercomputer resources to use effectively

**Generate Maps of SSH**

- Analyze regional and global dynamic SSH

**Data Assimilation**

- Eventually, SSH solutions will be assimilated into ROMS and evaluated to determine their ability to resolve mesoscale processes